A Double-Mode RR Lyrae Star with a Strong Fundamental Mode Component

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ABSTRACT

NSVS 5222076, a thirteenth magnitude star in the Northern Sky Variability Survey, was identified by Oaster as a possible new double-mode RR Lyrae star. We confirm the double-mode nature of NSVS 5222076, supplementing the survey data with new V band photometry. NSVS 5222076 has a fundamental mode period (P_0) of 0.4940 day and a first overtone period (P_1) of about 0.3668 day, giving a period ratio of $P_1/P_0 = 0.743$. In most double-mode RR Lyrae stars, the amplitude of the first overtone mode pulsation is greater than that of the fundamental mode pulsation. That is not true for this star. Its fundamental mode light curve has an amplitude twice as large as that of the first overtone mode, a ratio very rarely seen even among the double-mode RR Lyrae that do have relatively strong fundamental mode pulsation. Data from the literature are used to discuss the location in the Petersen diagram of double-mode RR Lyrae stars having strong fundamental mode pulsation. Such stars tend to occur toward the short period end of the Petersen diagram, and NSVS 5222076 is no exception to this rule.

Subject headings: (stars: variables:) RR Lyrae variable

1. Introduction

The Northern Sky Variability Survey (Wozniak et al. 2004) holds photometry on about 14 million objects brighter than apparent magnitude $V = 15.5$, which were accessible to the ROTSE-I telescope from its location in New Mexico. Oaster (2005) surveyed a selection of the brighter RR Lyrae stars within the Northern Sky Variability Survey (NSVS), identifying variables that might show either the Blazhko Effect or double-mode behavior. She identified

NSVS 5222076 ($\alpha_{2000} = 15^h46^m26^s$; $\delta_{2000} = +44^o18'45''$) as a possible new double-mode RR Lyrae. Double-mode RR Lyrae stars, also known as RRd or RR01 stars, exhibit simultaneous pulsation in the fundamental and first overtone radial modes (Smith 1995). In this paper, we use the NSVS data and additional V band observations to confirm the double-mode behavior of NSVS 5222076, and to show that it exhibits unusually strong fundamental mode pulsation for such a star. We also discuss the location in the Petersen diagram of double-mode stars that, like NSVS 5222076, have a fundamental mode amplitude as large or larger than the amplitude of their first overtone mode pulsation.

2. Photometry and Analysis

2.1. NSVS Data

We analyzed two sets of photometry of NSVS 5222076. First is the NSVS data for 5222076, obtained from the website at http://skydot.lanl.gov/nsvs/nsvs.php. The NSVS data include 218 observations taken between MJD 51274 and MJD 51559 with the ROTSE-I telescope, with a typical photometric uncertainty of $\pm$ 0.03 mag. The NSVS observations are tied to the Tycho V system (Wozniak et al. 2004), but, because the ROTSE-I observations are unfiltered, RR Lyrae light curves based on NSVS data do not exactly correspond to those that would be observed through standard Johnson V filters (Kinemuchi et al. 2005). A period search on the NSVS data using the Period04 program (Lenz & Breger 2005) found a primary period of 0.4940 day, with an uncertainty of about $\pm$ 0.0001 day. The light curve in the upper panel of Figure 1 shows the NSVS observations, folded with the 0.4940 day period after the NSVS MJDs have been converted to heliocentric Julian dates. The curve shows a scatter larger than expected from the photometric errors in the NSVS, a good indication that a single period does not fully describe the NSVS observations.

The 0.4940 day period and its first six harmonics were removed from the NSVS data, and the Period04 program was used to search for periodicities in the residuals. A period of 0.3669 days was identified, with an uncertainty of about $\pm$ 0.0002 days. A simultaneous fit was then made for the 0.4940 day period, the 0.3669 day period, and their six larger harmonics. The resultant fundamental mode and first overtone light curves are shown in Figure 2. The amplitude ratio for the fundamental and first overtone modes, A_0/A_1, is approximately 2. No significant evidence for additional periods was found.

2.2. V-Band Data

Because of the relatively small number of NSVS observations, we obtained new V band photometry of NSVS 5222076 using the 60-cm telescope of the Michigan State University campus observatory. Between JD 2453414 and JD 2453522, we obtained 1570 photometric observations on 16 nights using an Apogee Ap47p CCD camera. Aperture photometry was obtained differentially compared to star 1343-0291412, where the star identification is that of the United States Naval Observatory NOMAD catalog (http://www.nofs.navy.mil/nomad/), which merges data from several prior astrometric and photometric catalogs (Zacharias et al. 2004). The NOMAD compilation gives approximate V and B magnitudes of 13.2 and 13.6 for 1343-0291412, making it comparable in magnitude, though perhaps slightly redder than NSVS 5222076. NOMAD star 1344-0283988 was used as a check star. For it, the NOMAD compilation lists magnitudes of V = 13.63 and B = 14.20. The Guide Star Catalog 2 (GSC2.2) numbers for the comparison and check stars are N1321133346 and N132113394, respectively. In Table 1 we give heliocentric Julian Dates and differential magnitudes in the sense $\Delta V = V(5222076) - V(compstar)$ for the Michigan State University observations. The accuracy of each of the observations depends somewhat on the sky conditions at the time of observation, but is typically $\pm$ 0.015 mag.

We analyzed the V data in a fashion similar to that employed for the NSVS observations. We conducted a period search on the MSU photometry, again finding a primary period of 0.4940 $\pm$ 0.0001 day (frequency f_0= 2.0242). When the MSU observations are folded with this period, it is again clear that a single period does not by itself fully describe the light curve behavior (Figure 1, lower panel). We used Period04 to prewhiten the data to remove f_0 and its next six harmonics. A search on the prewhitened data identified a period of 0.3668 $\pm$ 0.0002 day (frequency f_1= 2.7265). These periods were identified as the fundamental and first overtone radial modes, respectively, and are very close to the values obtained from the NSVS data.

To see whether there were any additional periods present in the data, we used Period04 to simultaneously fit the f_0 and f_1 frequencies and their next six harmonics. In a further period search on this prewhitened data, we identified small contributions from combinations of f_0 and f_1.

The final fit is shown in Table 2, where only components having an amplitude greater than 0.005 mag are listed. The deconvolved light curves for the 0.3668 day period and the 0.4940 day period are shown in Figure 3.

The resultant amplitude ratio, A_0/A_1, is again 2.0. However, the V band data allow the light curve shape of each mode to be much more clearly seen. It is usually the first

overtone radial mode rather than the fundamental mode that is strongest among double-mode RR Lyrae stars. In such cases, the light curve shape of the fundamental mode is more symmetric than is usually seen for stars that pulsate solely in the fundamental mode (RRab stars). Here, however, we see the asymmetric light curve typical of RRab pulsators, with a rise to maximum much steeper than the decline to minimum. We also note in Figure 3, the appearance of a bump before maximum light in the light curve of the fundamental mode. Bumps before the rise to maximum are seen in many RRab light curves, though often not with the prominence shown in Figure 3. We also note that there seems to be some scatter in the deconvolved light curves beyond that expected of observational error alone. In the case of the fundamental mode light curve this is particularly apparent just before the beginning of the pre-rise bump.

The pre-rise bump in the light curves of RRab stars is usually believed to be a consequence of shock wave phenomena, though there has been debate over the relative roles of heating by infalling gas and of reflection of a compression wave at the boundary of the core (Gillet & Crowe 1988; Carney et al. 1992; Fokin & Gillet 1997). The bump is often more prominent in the light curves of RRab stars with large amplitudes. In the case of RR Lyrae, which has a light curve modulated in a 40-day Blazhko cycle, the bump is stronger when the amplitude of the light curve is larger (Walraven 1949; Kolenberg et al. 2005). It is tempting to attribute the pre-maximum bump in the fundamental mode light curve of NSVS 5222076 to the same cause. The interplay between the two pulsation modes might be expected to change the amount of the shock, perhaps resulting in the light curve scatter seen prior to the bump. A problem with this hypothesis is that the fundamental mode amplitude in NSVS 5222076 is smaller than that usually seen in RRab stars that have strong pre-rise bumps.

3. The Petersen Diagram

Double-mode RR Lyrae stars generally fall along a sequence in the Petersen diagram (Petersen 1973), in which the ratio of the periods is plotted against the fundamental mode period (see, for example, Figure 6b of Szabó et al. (2004)). In Figure 4 we have drawn two versions of the Petersen diagram. In the lower panel we have plotted double-mode RR Lyrae stars with published ratios of the fundamental to first overtone amplitude, $A0/A1$, that are smaller than 1.0. Not all identifications of double-mode RR Lyrae in the literature provide amplitude ratio information, but in Figure 4 we have been able to include data on double-mode stars in the Large Magellanic Cloud (Soszynski et al. 2003), the Sculptor dwarf spheroidal (Kovács 2001), the Draco dwarf spheroidal (Smith et al. 2005), M15 (Purdue et al. 1995; Nemec 1985), the galactic field (Wils & Otero 2005; Garcia-Melendo et al. 2001;

Clementini et al. 2000; Clement et al. 1991; Moskalik & Poretti 2003; Jerzykiewicz et al. 1982), and the Sagittarius dwarf spheroidal (Cseresnjes 2001).

In the upper panel of Figure 4 we have plotted double-mode RR Lyrae that have strong fundamental mode pulsation, with an amplitude $A0/A1$ greater than or equal to 1.0. We see that, while the variables with weaker fundamental mode pulsation span the entire range of periods, the stars with stronger fundamental mode pulsation occur only at fundamental periods shorter than 0.51 day, although even in that portion of the Petersen diagram the strong fundamental mode pulsators are in the minority. Although the shorter period end of the Petersen diagram is more densely populated by all double-mode RR Lyrae stars in Figure 4, the concentration of the strong fundamental mode pulsators to that region appears to be too strong to be a statistical fluke. Table 3 shows the number and percentage of double-mode RR Lyrae within this diagram that have $A0/A1$ greater than or equal to 1.0, dividing the sample into three subgroups based on fundamental mode period. Stars with $A0/A1$ greater than or equal to 1.0 account for 12 ± 2 percent of the complete sample, but the percentage rises at shorter periods and falls at longer periods. A chi squared test for equality of distribution indicates a less than 1 percent probability of obtaining the observed excess of strong fundamental mode pulsators at periods shorter than 0.47 day or the deficiency of such stars at periods longer than 0.51 day.

Of the 344 double-mode RR Lyrae stars used to construct figure 4, only seven have reported ratios $A0/A1$ greater than 1.5. Only three have a ratio greater than 1.8, making them comparable to NSVS 5222076. These three stars are all among the sample of double-mode RR Lyrae in the Large Magellanic Cloud. Not plotted in Figure 4 because of the large overlap with the Soszynski et al. (2003) dataset, the LMC double-mode stars identified by Alcock et al. (1997) also indicate that double-mode stars with a ratio $A0/A1$ approaching 2 are very rare.

One caveat ought to be noted. A large fraction of the RR Lyrae stars in this sample, particularly at periods shorter than 0.51 day, are located in the Large Magellanic Cloud. It is possible that the properties of the double-mode RR Lyrae stars are closely tied to the particular horizontal branch properties of their parent system. If that is the case, the correlations reported here may not be universal.

One might also wonder whether any of the field RR Lyrae stars of the Galaxy in Figure 4 might actually be double-mode Cepheids rather than double-mode RR Lyrae stars. As shown, for example, in Figure 1 of Soszynski et al. (2000), double-mode Cepheids in the Magellanic Clouds can have period ratios similar to the 0.74 seen among the RR Lyrae stars. However, in such cases, the fundamental mode periods are longer than 0.7 days, so that if there were Galactic Cepheids similar to those in the Magellanic Clouds, they would

be expected to fall off the long period end of Figure 4.

NSVS 5222076 is plotted as a cross in figure 4. It falls slightly to the small period ratio side of the general Petersen diagram trend, but is not greatly discrepant. We note the presence of three more discrepant stars in figure 4, all with reportedly strong fundamental mode components. The dark point in the upper panel at a ratio of 0.7493 represents one of the stars in the LMC sample. We have also plotted in figure 4 the locations of two double-mode RR Lyrae in M3, V13 and V200, which have unusually small reported period ratios (Clementini et al. 2004). One complication in the cases of these two stars is that Clementini et al. (2004) find evidence that the amplitude ratios of the two stars may change with time (though note the caution in Benko et al. (2005)). The issue of the extent to which the relative amplitudes of the two components in double-mode RR Lyrae stars can change over time remains to be established.

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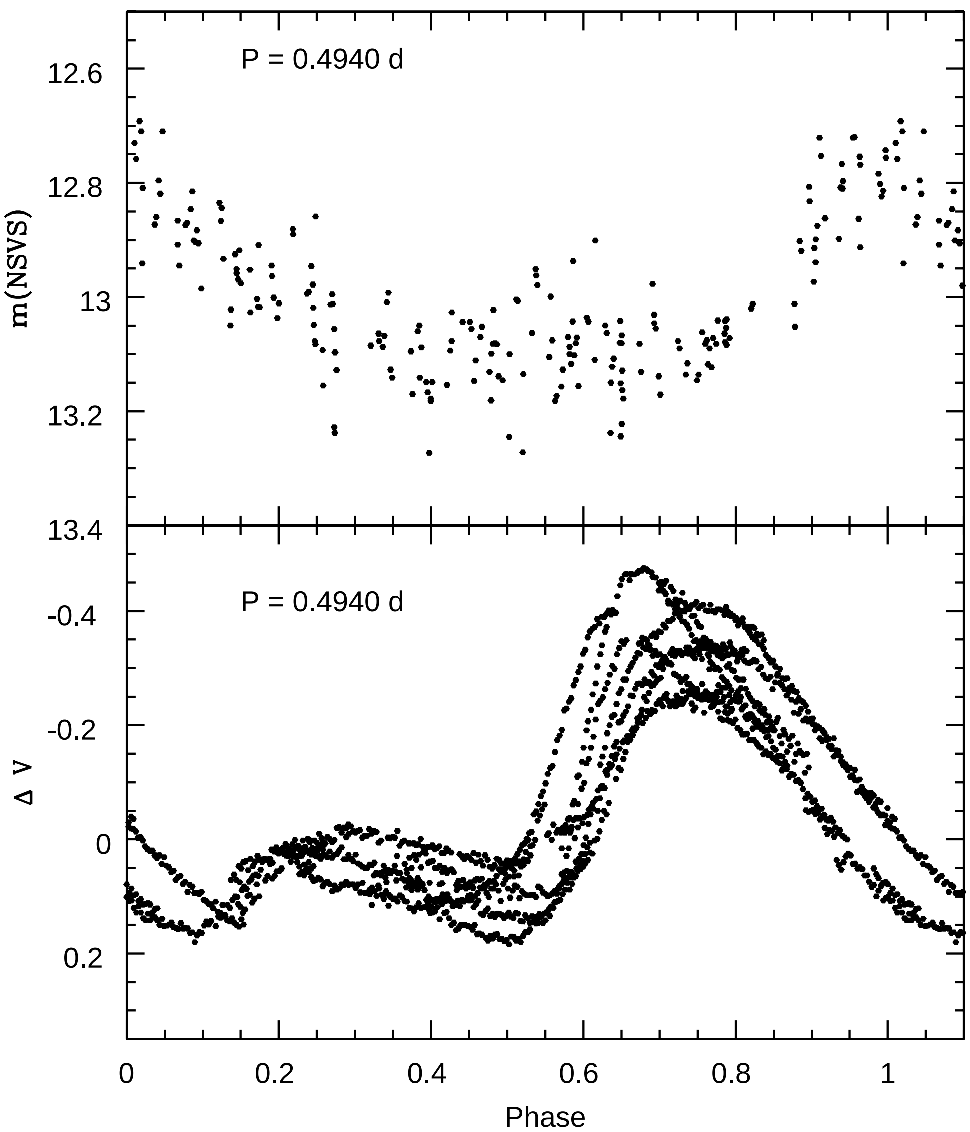

Fig. 1.— The upper panel shows the light curve of NSVS 5222076 based on observations in the Northern Sky Variability Survey, phased with a period of 0.4940 d. The lower panel shows the MSU V band data, phased with the same period.

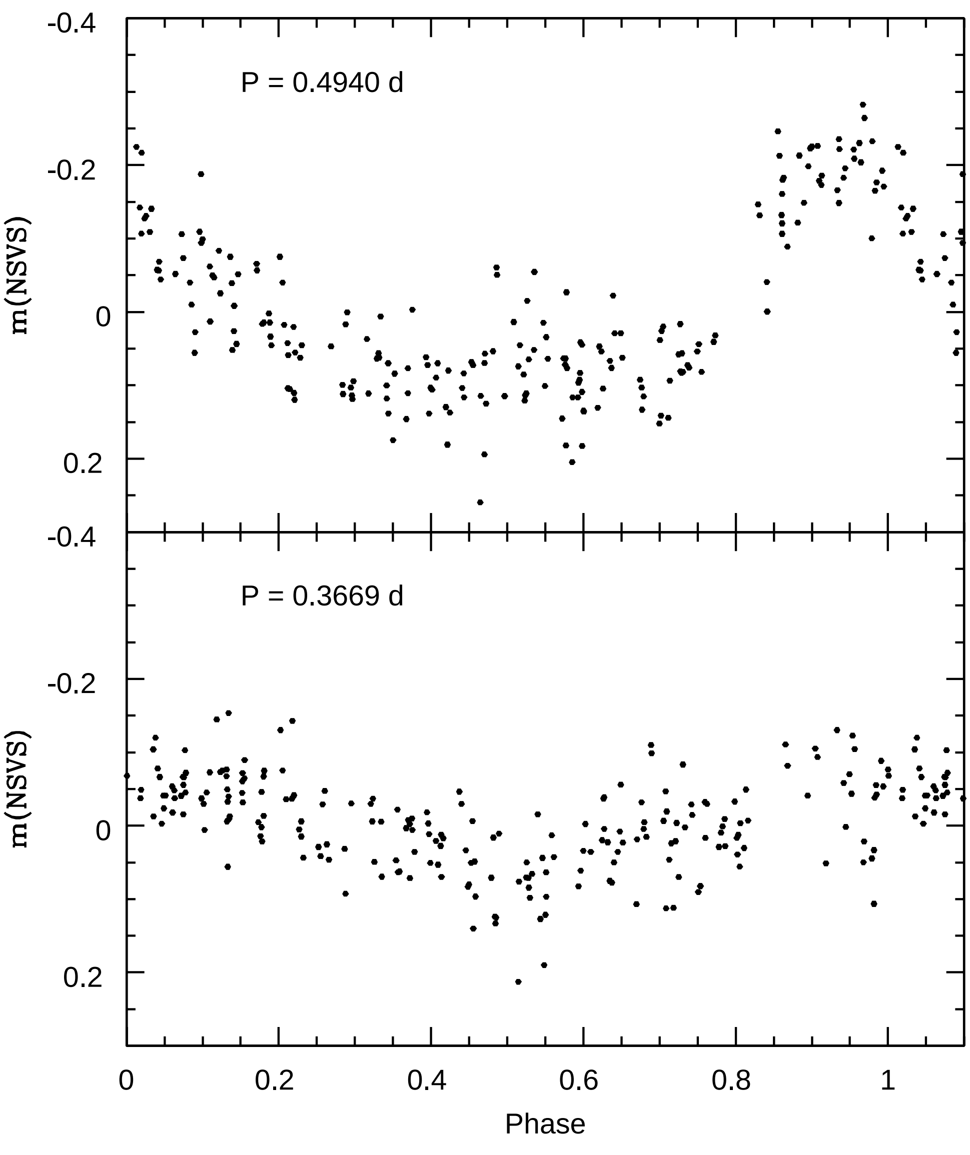

Fig. 2.— Fundamental mode and first overtone mode light curves of NSVS 5222076, based upon NSVS data, and phased with the indicated periods.

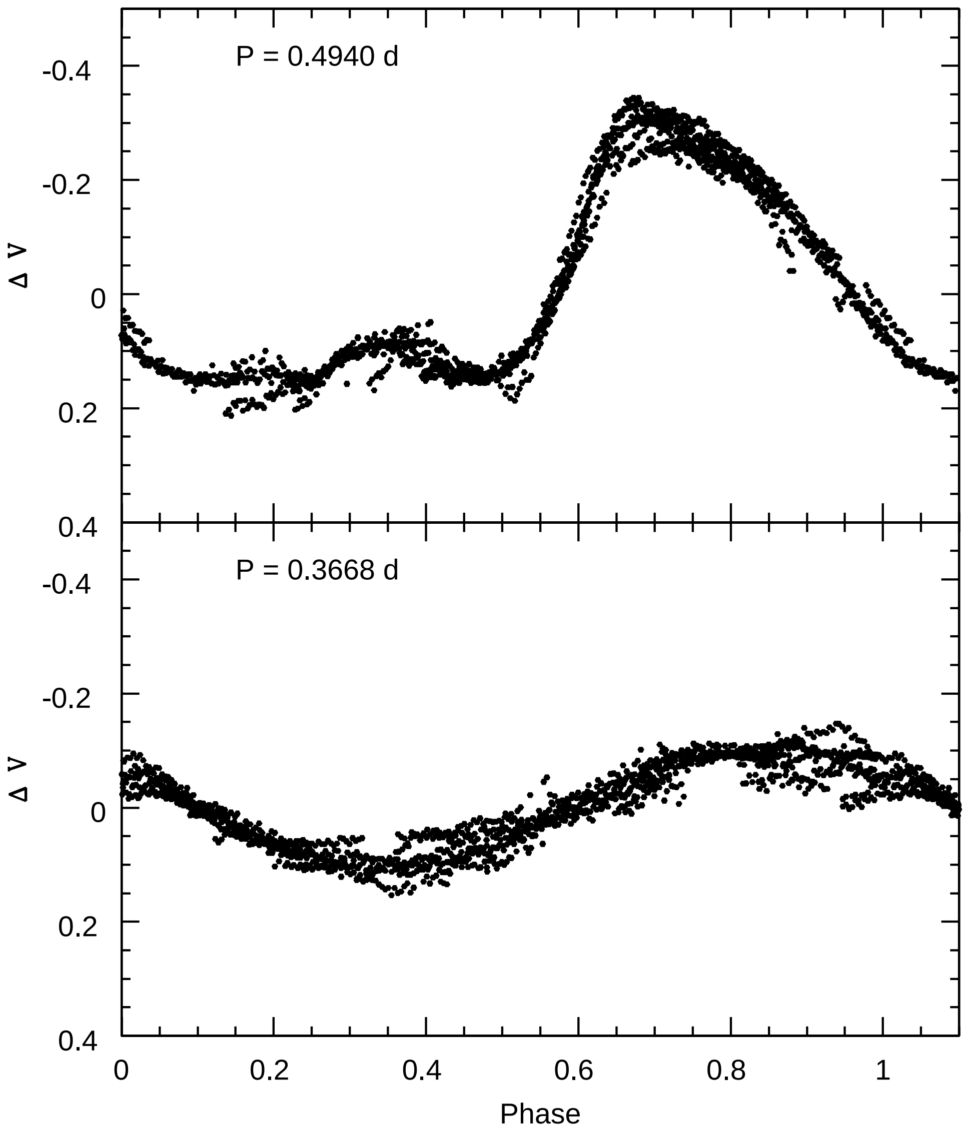

Fig. 3.— Fundamental mode and first overtone mode light curves of NSVS 5222076, based on Michigan State University data.

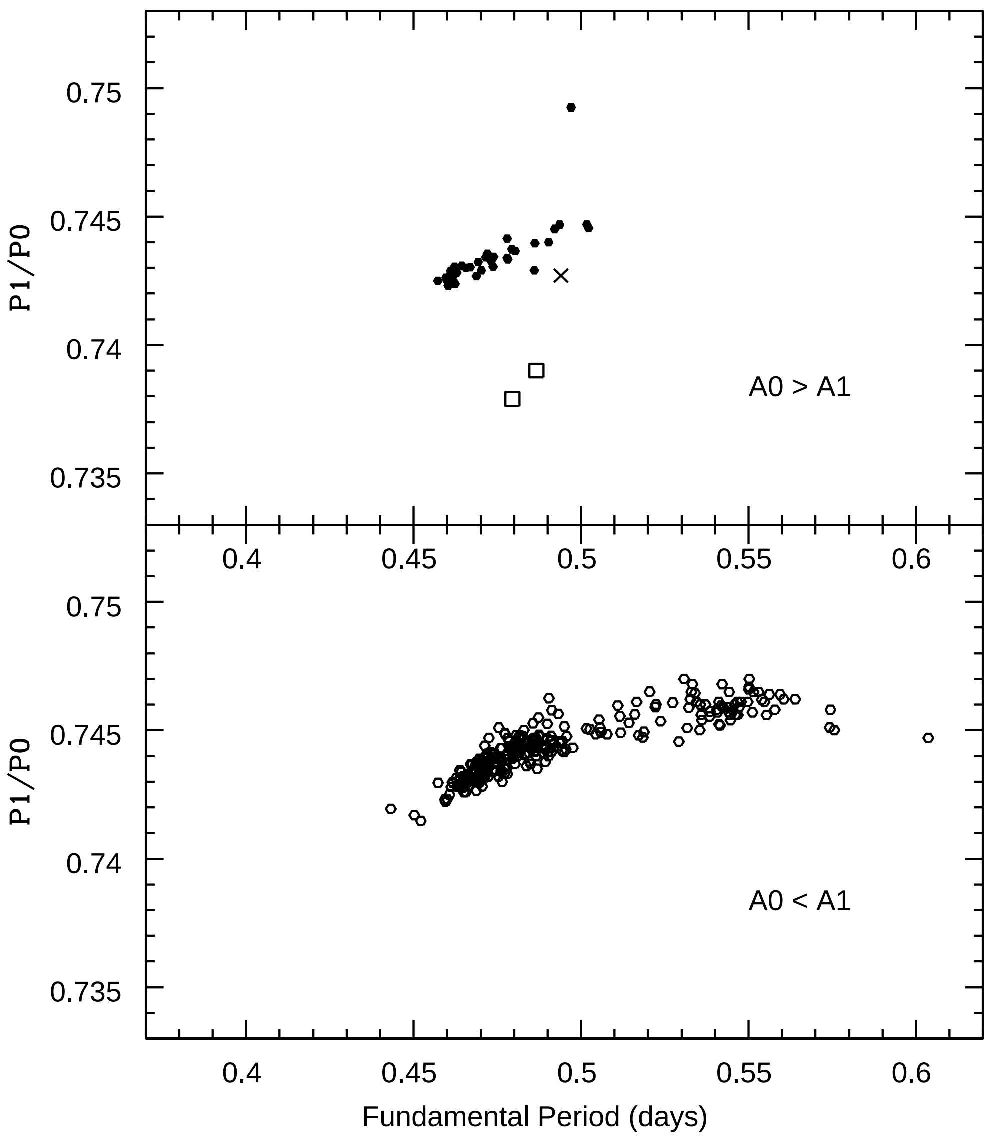

Fig. 4.— Petersen diagrams for a sample of double mode RR Lyrae from the literature for which amplitude information is available. The upper panel depicts double-mode stars for which the fundamental mode amplitude, $A0$, is stronger than the first overtone mode amplitude, $A1$. Variables with weaker fundamental mode amplitudes are plotted in the lower panel. In the upper panel, X marks the location of NSVS 5222076 and the two open squares indicate the places of two unusual double-mode RR Lyrae in the globular cluster M3.

Table 1. CCD Photometry (Michigan State University)

HJD	ΔV
2453414.8263	-0.233
2453414.8275	-0.251
2453414.8287	-0.255
2453414.8299	-0.243

Note. — The complete version of this table is in the electronic edition of the Publications. The printed edition contains only a sample.

Table 2. Fit to V Band Data

Frequency (c/d)	Ampl. (mag)
2.0242 ($= f_0$)	0.203
$2f_0$	0.088
$3f_0$	0.045
$4f_0$	0.019
$5f_0$	0.014
$6f_0$	0.008
$7f_0$	0.005
2.7265 ($=f_1$)	0.105
$2f_1$	0.010
$3f_1$	0.006
$f_0 + f_1$	0.021
$2f_0 + f_1$	0.036
$3f_0 + f_1$	0.018
$f_0 - f_1$	0.024

Table 3. RRd Stars with $A0/A1 \geq 1.0$

Fundamental Period (days)	Number	Percentage
< 0.47	21	24
0.47 – 0.51	20	11
> 0.51	0	0
All periods	41	12